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Design of a Smart Adaptive Control System

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Abstract: In industrial processes, it is necessary to maintain the user-specified control performance in order to achieve desired productivity. This paper describes a design scheme of smart adaptive controller based on the above strategy. In the proposed method, variance of control error and input are evaluated on-line. Moreover, control parameters are adjusted only when the user-specified control performance can not be obtained. Control parameters are calculated directly from closed-loop data and they are adjusted by 1-parameter tuning. The effectiveness of the proposed method is verified by using a simulation example and experiment of temperature control system.

Keywords: PID Control, Minimum variance control, Performance evaluation, Time varying systems, Least-squares method.

1. INTRODUCTION

In process industries, it is very important to keep the desired control performance from the viewpoint of saving energy and improving quality of product. However, it is difficult to achieve desired performance for time-variant system. Therefore, it is needed that control parameters are adjusted on-line like self-tuning control[Clarke et al. (1979); Wellstead et al. (1991); Yamamoto et al. (2004)] and adaptive control[Astrom (1983, 1989)]. However, in steady state, control parameters are not needed to be adjusted in every step because of computational cost and reliability of control parameters. For this reason, it is better to adjust control parameters only when control performance becomes unsatisfactory. Consequently, the idea of so-called 'Tuning on Demand' appeared, in which the control parameters will be adjusted only when control performance evaluation is insufficient. In other words, performance-adaptive control[Yamamoto et al. (2008)], which integrates 'control performance evaluation' and 'control system design', becomes more necessary.

There are two methods for calculating control parameters. One is based on system model and the other is based on closed-loop data without system model[Hjalmarsson et al. (1998); Campi et al. (2002); Kaneko et al. (2014); Wakitani et al. (2012)]. The latter method's advantage is a low computational cost.

In this paper, two aspects are considered, they are 'control performance evaluation using closed-loop data' and 'how to adjust control parameters'. In particular, control performance is improved by 1-parameter tuning based on the Generalized Minimum Variance Control: GMVC without system model[Wakitani et al. (2012)]. The 1-parameter tuning is simple to maintain control performance because of single parameter. The features of the proposed method are as follows; (1) 'Evaluate control performance' and 'Design control system' use only closed-loop data. (2) Adjust control parameters effectively by 1-parameter tuning. This proposed control system is called a smart adaptive control system because control performance evaluation and adjustment control parameters are worked automatically.

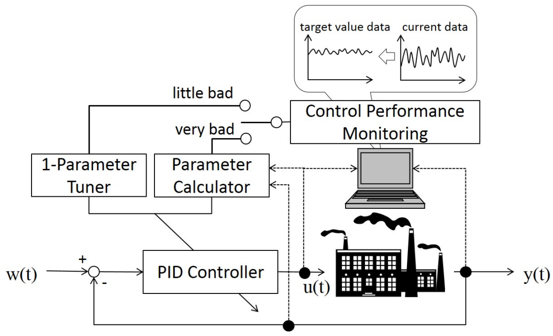

Fig. 1. Schematic diagram of the smart adaptive controller.

2. DESIGN OF SMART ADAPTIVE PID CONTROLLER

2.1 Overview of the control system

Fig. 1 shows the schematic diagram of a smart adaptive PID control system. First, a desired control performance ('variance of the control error in the steady state' and 'variance of the control input variation') is set in advance. Second, in the 'Control Performance Monitoring', the current control performance and the desired control performance are compared. Then, the PID controller is adjusted if the control performance becomes worse. First, '1-Parameter Tuner' works to adjust PID parameters. On the other hand, 'Parameter Calculator' works only when the characteristics of the system are changed significantly. In the next section, GMV-PID[Wakitani et al. (2012)], a PID controller based on GMVC, will be introduced.

2.2 Design of a GMV-PID control system

The controlled object can be described by the following equation:

$$A(z^{-1})y(t) = z^{-1}B(z^{-1})u(t) + \xi(t)/\Delta \tag{1}$$

$$\left.\begin{array}{l} A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} \\ B(z^{-1}) = b_0 + b_1 z^{-1} + \ldots + b_m z^{-m} \end{array}\right\}. \tag{2}$$

In equation (1), $u(t)$ is the control input, $y(t)$ is the system output, ξ(t) shows Gaussian white noise which has zero mean and covariance σ^2. In addition, z^{-1} is the back shift operator which implies $z^{-1}y(t)$=$y(t-1)$. Δ denotes a difference operator and Δ:= $1-z^{-1}$ is defined. Additionaly, m expresses the order of $B(z^{-1})$.

In the system of equation (1), the GMVC law is derived based on the minimization of the following criterion:

$$J = E\left[\phi^2(t+1)\right], \tag{3}$$

where $\phi(t+1)$ is a generalized output given by the following equation:

$$\phi(t+1) := P(z^{-1})y(t+1) + \lambda\Delta u(t) - P(1)w(t), \tag{4}$$

where w(t) denotes the reference value of the step. In addition, λ is the weighting factor for variation of input and it is an user-specified parameter. The Diophantine equation (5) is introduced by the formula:

$$P(z^{-1}) = \Delta A(z^{-1}) + z^{-1}F(z^{-1}), \tag{5}$$

where

$$F(z^{-1}) = f_0 + f_1 z^{-1} + f_2 z^{-2}. \tag{6}$$

In addition, $P(z^{-1})$ is a polynomial and it is designed based on the reference design [Yamamoto et al. (2004)] as follows:

$$P(z^{-1}) = 1 + p_1 z^{-1} + p_2 z^{-1} \tag{7}$$

$$\left.\begin{array}{l} p_1 = -2e^{-\frac{\rho}{2\mu}}\cos\left(\dfrac{\sqrt{4\mu-1}}{2\mu}\rho\right) \\ p_2 = e^{-\frac{\rho}{\mu}} \\ \rho := T_s/\sigma \\ \mu := 0.25(1-\delta) + 0.51\delta \end{array}\right\}, \tag{8}$$

where σ is a parameter related to the rise-time and δ is a parameter related to the damping oscillation. Designers set them arbitrarily. σ denotes the time when output reaches about 60% of the step reference value. Furthermore, δ is set between $0 \le \delta \le 2.0$ desirably. In particular, $\delta = 0$ indicates the response of Butterworth model and $\delta = 1.0$ indicates the response of Binominal model.

From equation (1), (4) and (5), the one-step ahead prediction of the generalized output at time t is expressed by the following equation:

$$\begin{aligned} \phi(t+1|t) = F(z^{-1})y(t) + \left\{B(z^{-1}) + \lambda\right\}\Delta u(t) \\ -P(1)w(t) + \xi(t+1). \end{aligned} \tag{9}$$

Here, optimal one-step ahead prediction value at time t is defined as follows:

$$\begin{aligned} \hat{\phi}(t+1|t) := F(z^{-1})y(t) + \left\{B(z^{-1}) + \lambda\right\}\Delta u(t) \\ -P(1)w(t). \end{aligned} \tag{10}$$

In addition, the following equation is obtained from equation (9) and (10).

$$\phi(t+1|t) = \hat{\phi}(t+1|t) + \xi(t+1). \tag{11}$$

From equation (3) and (11), the GMVC law (12) is derived as a criterion J which is minimized by the $\hat{\phi}(t+1|t) = 0$.

$$\Delta u(t) = \frac{P(1)}{B(z^{-1}) + \lambda}w(t) - \frac{F(z^{-1})}{B(z^{-1}) + \lambda}y(t). \tag{12}$$

In this paper, the control parameters are calculated directly based on a implicit method of GMVC without the system identification. It is obtained from the closed-loop data in one time. More specifically, prediction error between generalized output and optimal predicted value is defined as follows:

$$\varepsilon(t+1) := \phi(t+1) - \hat{\phi}(t+1|t). \tag{13}$$

The parameters of $F(z^{-1})$ and $B(z^{-1})$ are calculated directly from closed-loop data by applying the least square method to minimum equation (13)[Wellstead et al. (1991)]. It is possible to design the GMVC system directly based on closed-loop data by applying $F(z^{-1})$ and $B(z^{-1})$ to equation (12).

Next, the PID parameters are replaced by the implicit GMVC [Yamamoto et al. (2004, 2008); Wakitani et al. (2012)]. First of all, consider the velocity type PID control law in the following equation:

$$\Delta u(t) = \frac{k_c T_s}{T_I}e(t) - k_c\left(\Delta + \frac{T_D}{T_s}\Delta^2\right), \tag{14}$$

where

$$e(t) := w(t) - y(t). \tag{15}$$

Respectively, k_c, T_I and T_D respectively denote the proportional gain, integral time, and derivative time. Then, the following equation obtained by replacing the steady-state term $B(1)$ to the polynomial $B(z^{-1})$ in equation (12).

$$\Delta u(t) = \frac{P(1)}{B(1) + \lambda}w(t) - \frac{F(z^{-1})}{B(1) + \lambda}y(t). \tag{16}$$

Comparing the coefficients of equation (14) and (16), the PID parameters can approximately be replaced by GMVC parameters as follows:

$$\left.\begin{aligned} k_c &= -\frac{f_1+2f_2}{B(1)+\lambda} \\ T_I &= -\frac{f_1+2f_2}{f_0+f_1+f_2}T_s \\ T_D &= -\frac{f_2}{f_1+2f_2}T_s \end{aligned}\right\}. \tag{17}$$

2.3 Adjustment of λ based on the control performance evaluation

In this paper, λ in the GMV-PID is adjusted based on 'variance of the control error' and 'variance of the control input variation'. In GMV-PID, a trade-off curve shown in Fig.2 is obtained along with λ. The vertical axis shows the variance of control error in steady-state $E[e^2(t)]$, the horizontal axis shows the variance of the control input variation $E[(\Delta u(t))^2]$. Fig.2 shows it is simple to adjust control performance by λ. 'A', 'B' and 'C' regions are described later.

In Fig.2, $E[e^2(t)]$ and $E[(\Delta u(t))^2]$ are adjusted based on λ. At this time, it is important to determine λ. First, the user specifies the desired variance of control error: σ_e^2. And then λ is determined by the trade-off curve. In Fig.2, the point '$\bullet$' is desirable control performance ($\sigma_e^2 = 0.1$). Consequently, if current control performance can be plotted within 'A' region, which means desired control performance is obtained because current performance is smaller than desired performance '$\bullet$'.

However, it can be considered that the desired control performance is not obtained due to the time varying system. It implies the current control performance is moved to 'B' or 'C' region from 'A' region in Fig.2. Therefore, this paper presents the method which maintains the desired control performance if current control performance can be plotted in (1) 'B' region and (2) 'C' region. (1) If current control performance is in 'B' region, control parameters are adjusted by 1-parameter:λ tuning assume that control performance is following trade-off curve. (2) If current control performance is in 'C' region, it is difficult to achieve desired control performance by 1-parameter tuning. Therefore, control parameters are recalculated directly from closed-loop data in *2.2*. In addition, λ_d is the width between trade-off curve and the boundary line of 'B' and 'C' regions.

From [Yamamoto et al. (2008)], in order to get trade-off curve, the variance of control error $e(t)$ and the variance of input variation $\Delta u(t)$ can be calculated by the following equation using H_2 norm $||\cdot||_2$:

$$E[e^2(t)] = \left\|-\frac{1}{T(z^{-1})}\right\|_2^2 \sigma_\xi^2 \tag{18}$$

$$E[(\Delta u(t))^2] = \left\|-\frac{C(z^{-1})}{T(z^{-1})}\right\|_2^2 \sigma_\xi^2, \tag{19}$$

where

$$T(z^{-1}) := \Delta A(z^{-1}) + z^{-1}B(z^{-1})C(z^{-1}) \tag{20}$$

$$C(z^{-1}) := \frac{F(z^{-1})}{B(1)+\lambda}. \tag{21}$$

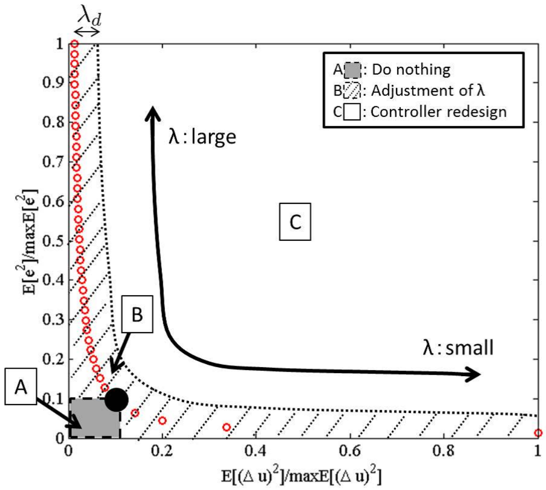

Fig. 2. Trade-off curve indicated by changing λ.

In equation (20), system parameter $A(z^{-1})$ is required for calculating $T(z^{-1})$. Therefore, the equation (20) can be rewritten as following equation:

$$T(z^{-1}) = P(z^{-1}) + z^{-1}\left\{B(z^{-1})C(z^{-1}) - F(z^{-1})\right\} \tag{22}$$

where $F(z^{-1})$ and $B(z^{-1})$ are calculated by minimization of equation (13) and equation (5). Trade-off curve is gotten without system parameter $A(z^{-1})$ from equation (21), (22).

In addition, σ_ξ shows the covariance of Gaussian white noise. However, the value of σ_ξ is unknown. Therefore, σ_ε, the standard deviation of ε in equation (13), is used instead of σ_ξ.

2.4 Control algorithm

The algorithm is shown by using Fig. 2. In the proposed algorithm, N is the number of data. Moreover, each variance is calculated as the time average assuming that ergodicity holds.

- 1^o Obtain closed-loop data by stable control.
- 2^o Calculate $F(z^{-1})$ and $B(z^{-1})$ from closed-loop data based on GMV-PID.
- 3^o Calculate σ_ε which is the standard deviation in equation (13).
- 4^o Calculate the equation (18) and (19) to get the trade-off curve of Fig. 2.
- 5^o Calculate the point $(E[(\Delta u(t))^2]_{\min}, E[e^2(t)]_{\min}$: '$\bullet$' in Fig. 2 by the desired control error variance: σ_e^2. Adopt λ which is calculated from trade-off curve to PID parameters in equation (17).
- 6^o The following criterion J_r is obtained by using $E[(\Delta u(t))^2]_{\min}$ and $E[e^2(t)]_{\min}$ as the slope of the straight line passing through the origin and '$\bullet$' in Fig. 2.

$$J_r = \frac{E[e^2(t)]_{\min}}{E[(\Delta u(t))^2]_{\min}} \tag{23}$$

- 7^o During N steps, control by PID controller which is employed in 5^o.
- 8^o Calculate the current variance of control error $E[e^2(t)]$ and variance of control input variation $E[(\Delta u(t))^2]$ by N data from time: t before the N steps.

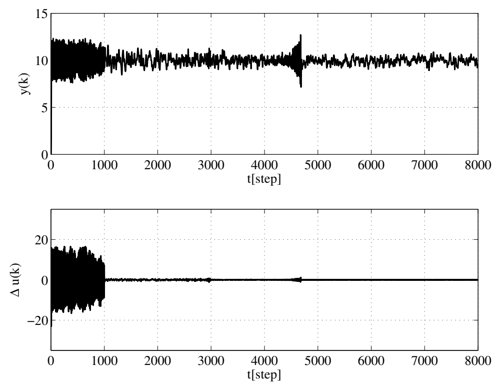

Fig. 3. Control result by proposed control scheme in the case of $\sigma_e^2 = 0.4$.

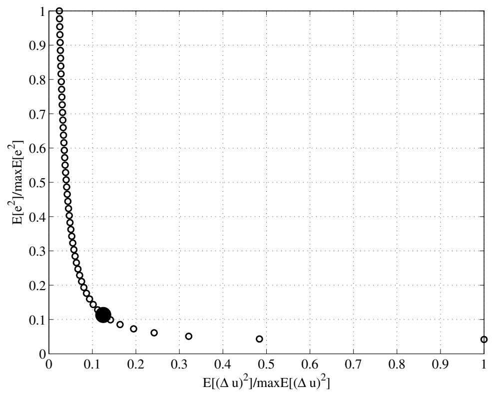

Fig. 4. Trade-off curve indicated by changing λ.

Next, calculate the following current criterion $J(t)$ by $E[(\Delta u(t))^2]$ and $E[e^2(t)]$ same as 6^o.

$$J(t) = \frac{E[e^2(t)]}{E[(\Delta u(t))^2]} \tag{24}$$

9^o If the current variance $E[(\Delta u(t))^2]$ and $E[e^2(t)]$ of 8^o is located in 'A' region, Go to 11^o. If it is located in 'B' region, Go to 10^o. If it is located in 'C' region, Go to 2^o (Use N data when going to 2^o).

10^o 1-parameter:λ is tuned and then adopted the PID gain corresponding to the λ. At this time, λ is increased or decreased by $\Delta\lambda$ in order to close current performance to '•'. In concretely, If satisfying following equation, $\lambda = \lambda + \Delta\lambda$. Otherwise, $\lambda = \lambda - \Delta\lambda$.

$$J(t) < J_r \tag{25}$$

11^o $t = t + 1$

12^o Return 8^o.

3. NUMERICAL EXAMPLE

It is considered that the proposed method is applied for initial setting of PID parameters. In addition, $w(t) = 10$, $m = 3$, $N = 500$, $\lambda_d = 0.03$, $\Delta\lambda = 0.02$ are set. First, consider the following system:

$$G(s) = \frac{K}{1 + Ts} e^{-Ls}, \tag{26}$$

where $T = 100$, $K = 0.9$ and $L = 15$. Discretize the equation (26) by sampling time $T_s = 5.0[s]$ and the model to be controlled by adding a Gaussian white noise with mean 0 and covariance 0.001 as the modeling error. Furthermore, the system gain and the time constant are changed between 2001[step] to 5000[step] as follows:

$$T = \begin{cases} 100 \ (0 < t \leq 2000) \\ 100 - \dfrac{50(t - 2000)}{3000} \ (2001 < t \leq 5000) \\ 50 \ (5000 < t \leq 8000) \end{cases} \tag{27}$$

$$K = \begin{cases} 0.9 \ (0 < t \leq 2000) \\ 0.9 + \dfrac{5.1(t - 2000)}{3000} \ (2001 < t \leq 5000) \\ 6 \ (5000 < t \leq 8000) \end{cases} . \tag{28}$$

The proposed method is applied for the controlled system. The control results are shown in Fig.3. In addition, $\sigma_e^2 = 0.4$ is set as the desired variance of control error. In the first 1000[step], in order to obtain closed-loop data , the initial PID parameters were set as follows:

$$k_c = 8.89, T_I = 30.0, T_D = 7.50. \tag{29}$$

which is calculated by Ziegler-Nichols(ZN) method[Ziegler et al. (1942)].

Next, the proposed controller is performed at $t = 1000$[step]. In addition, $P(z^{-1})$ is designed as the following equation:

$$P(z^{-1}) = 1 - 1.64z^{-1} + 0.67z^{-2}. \tag{30}$$

In this case, the trade-off curve in Fig.4 obtained from closed-loop data. However, '•' denotes the desired control performance. After 1000[step], variance of control error is 0.22 and desired control performance ($\sigma_e^2 = 0.4$) is achieved. Fig. 5 and Fig. 6 show the trajectories of PID parameters and λ respectively. Fig. 7 shows the trajectories that variance of control error and input.

In Fig.5, T_I and T_D were adjusted only one time at 4683[step], however, k_c was adjusted a lot of times before 4683[step]. The reason is that λ is adjusted in 10^o and only k_c depends on λ in equation (17). These are indicated in Fig. 7. On the one hand, the variance of control input variation $\mathrm{E}[\Delta u(t)^2]$ only becomes bigger than desired $\mathrm{E}[\Delta u(t)^2]_{\min}$ around 3000[step]. Therefore, at that time, '1-parameter tuning' is functioned at first. On the other hand, at 4683[step], both $\mathrm{E}[\Delta e(t)^2]$ and $\mathrm{E}[\Delta u(t)^2]$ become much bigger than $\mathrm{E}[\Delta e(t)^2]_{\min}$ and $\mathrm{E}[\Delta u(t)^2]_{\min}$ respectively. Consequently, 'control parameters redesign' is functioned. From this result, PID parameters could be adjusted efficiently for the time-variant system.

Finally, Fig.8 shows the control result by only ZN method[Ziegler et al. (1942)] for the purpose of comparison. It is impossible to control time-variant system by the fixed PID parameters. From the above results, the effectiveness of the proposed method is verified.

4. APPLICATION TO TEMPERATURE CONTROL SYSTEM

The proposed method(only 1-parameter tuning) is applied to temperature control system in Fig. 9.

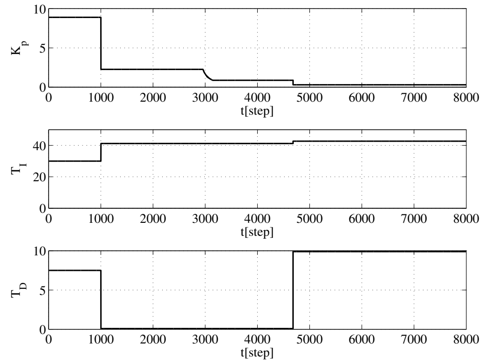

Fig. 5. Trajectories of PID parameters corresponding to Fig.3.

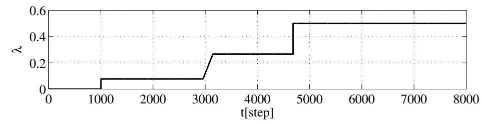

Fig. 6. Trajectories of the user-specified parameter λ corresponding to Fig.3.

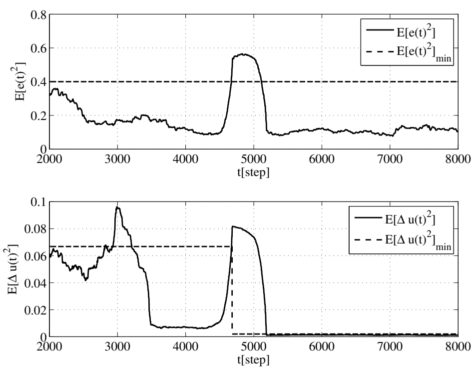

Fig. 7. Trajectories of variance of $e(t)$ and $\Delta u(t)$ corresponding to Fig.3.

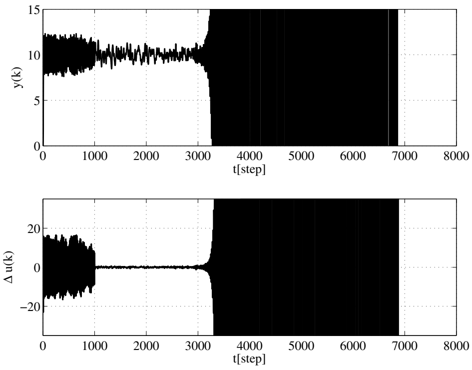

Fig. 8. Control result using the fixed PID parameters which are tuned by the ZN method.

4.1 System configuration

In this experiment, the controlled objective is to control water temperature by adjusting the quantity of hot water.

In Fig. 9, system output $y(t)$ is water temperature[$^\circ C$], control input $u_1(t)$ is hot watter valve position[%], and $u_2(t)$ shows the cold watter valve position[%]. Additionally, PT is a platinum resistance temperature detectors.

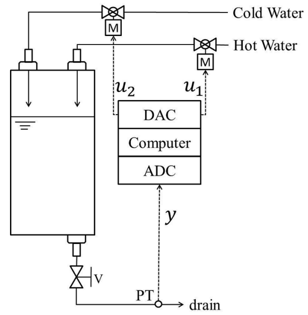

Fig. 9. Schematic figure of temperature control system.

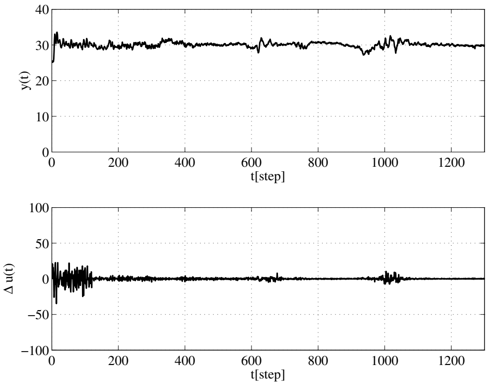

Fig. 10. Control result by the proposed control scheme in the case of $\sigma_e^2 = 0.5$.

Water temperature $y(t)$ is measured by PT and sent to computer. computer receives the signal by a A/D converter. After the proposed algorithm was run in the computer, electrical signal was converted by a D/A converter and sent to valve. Hot water valve position $u_1(t)$ is adjusted. Thus, the quantity of hot water is adjusted by $u_1(t)$.

In this experiment, control input is $u_1(t)$ and control output is $y(t)$. Note that the cold water valve position u_2[%] is used to change the characteristics of controlled system.

4.2 Control result

The sampling time is set as $T_s = 5.0$[s]. In addition, the cold water valve position is changed as follows:

$$u_2(t) = \begin{cases} 50 \ (0 < t \leq 300) \\ 50 - \dfrac{30(t-300)}{700} \ (300 < t \leq 1000) \\ 20 \ (1000 < t \leq 1300) \end{cases} . \quad (31)$$

At this time, $w(t) = 10$, $m = 3$, $N = 500$, $\lambda_d = 0.03$, $\Delta\lambda = 0.02$ were set and $P(z^{-1})$ was designed as the following equation:

$$P(z^{-1}) = 1 - 1.0268z^{-1} + 0.2636z^{-2}. \quad (32)$$

Furthermore, $\sigma_e^2 = 0.5$ was set as the desired variance of control error.

Fig. 10 shows the control result and Fig. 11 shows the trajectories of PID parameters. In Fig. 10 and Fig. 11, in order to obtain closed-loop data, the initial PID parameters in the first 100[step] are set as follows:

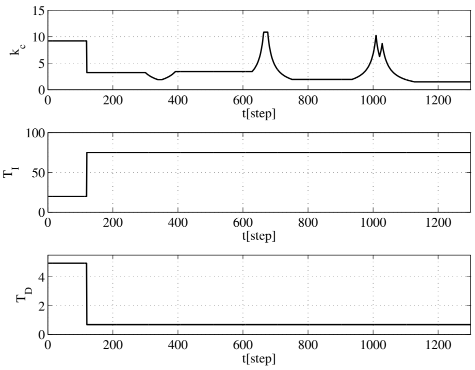

Fig. 11. Trajectories of PID parameters corresponding to Fig. 10.

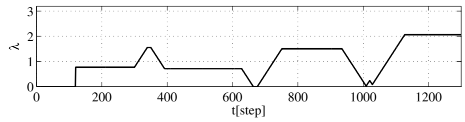

Fig. 12. Trajectories of λ corresponding to Fig. 10.

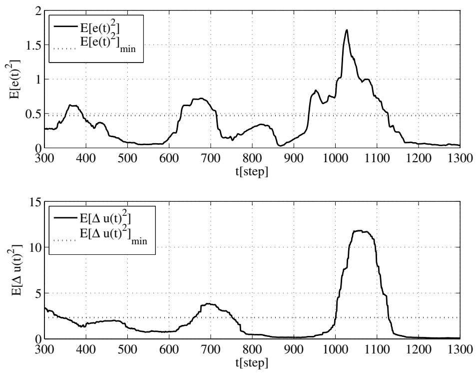

Fig. 13. Trajectories of the control performance corresponding to Fig. 10.

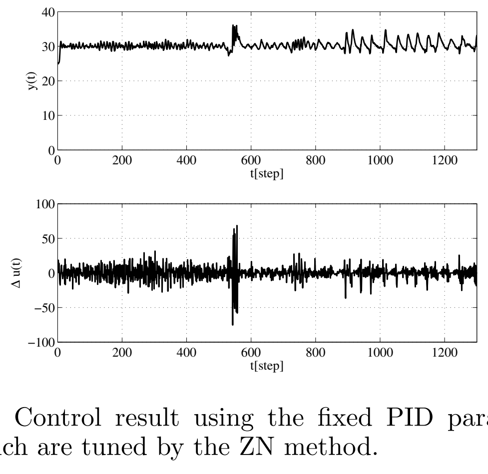

Fig. 14. Control result using the fixed PID parameters which are tuned by the ZN method.

$$k_c = 9.21, T_I = 19.75, T_D = 4.94 \tag{33}$$

which is calculated by ZN method. The proposed method(only '1-parameter tuning') is performed at $t = 100$[step]. After 100[step], variance of control error is 0.41 and desired control performance($\sigma_e^2 = 0.5$) is achieved.

Next, Fig. 12 shows the trajectories of λ and Fig. 13 shows trajectories of variances. Only λ is adjusted in this experiment which means that only k_c is adjusted because of equation (17). In Fig. 12, λ is adjusted around 300, 650 and 950[step] because $\mathrm{E}[\Delta e(t)^2]$ and $\mathrm{E}[\Delta u(t)^2]$ become much bigger than $\mathrm{E}[\Delta e(t)^2]_{\min}$ and $\mathrm{E}[\Delta u(t)^2]_{\min}$ respectively in Fig. 13. In Fig. 10, temperature became lower around 650 and 950[step].

Finally, Fig.14 shows the control result by only ZN method for the purpose of comparison. The variance of control error was 1.30 which did not achieve desired control performance ($\sigma_e^2 = 0.5$). From the above results, the effectiveness of 1-parameter tuning is verified.

5. CONCLUSION

This paper has proposed a smart adaptive control system for time-variant system. The main feature is that an user-specified parameter λ is automatically adjusted without the system identification in order to achieve the desired control performance. In addition, the effectiveness of the proposed method has been verified by numerical simulation and experiment. In the experiment, the effectiveness of '1-parameter tuning ' has been confirmed.

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